



TFAWS
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Four Bed Molecular Sieve – Exploration (4BMS-X) Heater Design and Analysis

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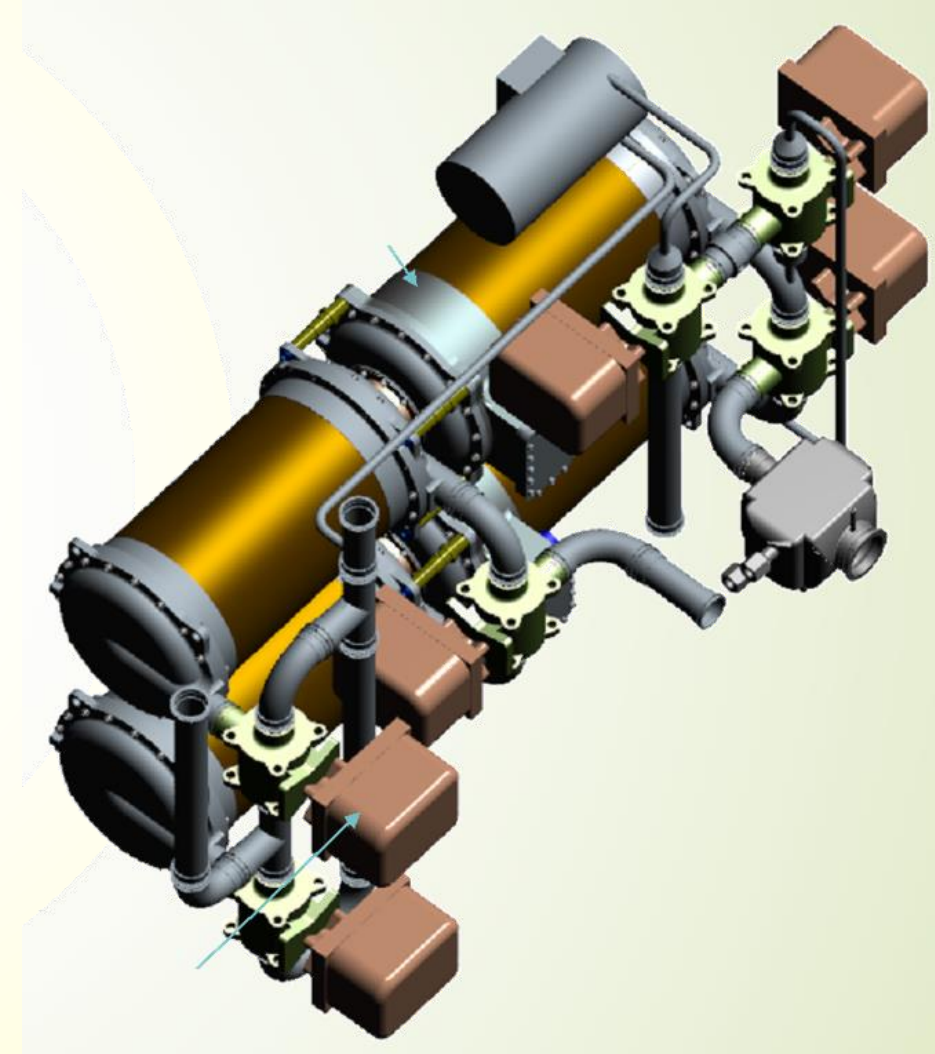
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Introduction



- A CO₂ removal technology development roadmap for exploration has been formulated to advance both existing and new technologies to an on-orbit evaluation via an ISS flight demonstration early in the next decade.
- As part of the development process, the 4BMS-X (Four Bed Molecular Sieve for Exploration) will introduce a number of potential improvements over existing ISS CDRA (Carbon Dioxide Removal Assembly) technology including cylindrical sorbent beds and an improved heater core.
- The design and analysis of an optimized heater core for the 4BMS-X CO₂ sorbent beds is presented.

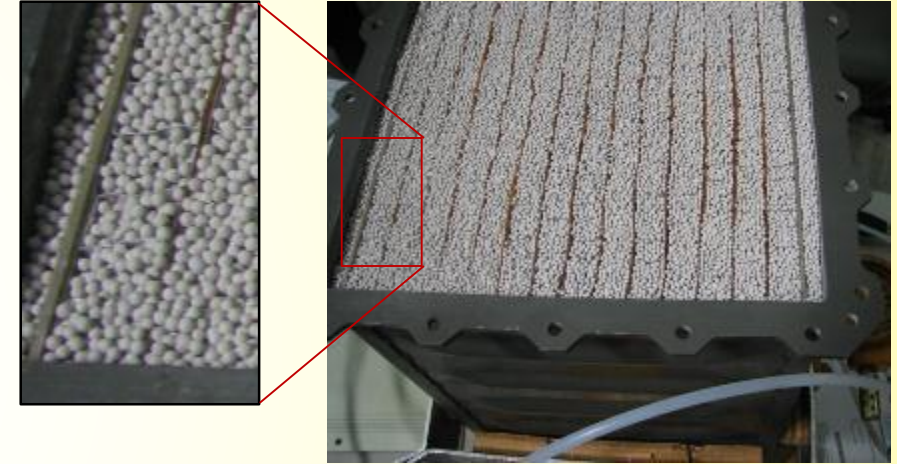


4BMS-X Concept



Adsorption Physics

- Adsorption is the adhesion of molecules of gas, liquid, or dissolved solids to a surface.
- This process creates a film of the adsorbate (the molecules or atoms being accumulated) on the surface of the adsorbent. It differs from absorption, in which a fluid permeates or is dissolved by a liquid or solid.
- In the 4BMS-X a sorbent (Zeolite 13X) is used to capture molecules of CO_2 . The trapped CO_2 can be removed or “desorbed” through the application of heat and partial vacuum.
- Many CO_2 sorbents also have a strong affinity for water vapor, which must be removed upstream of the CO_2 sorbent bed.



ISS Carbon Dioxide Removal Assembly (CDRA)
CO₂ Sorbent Bed



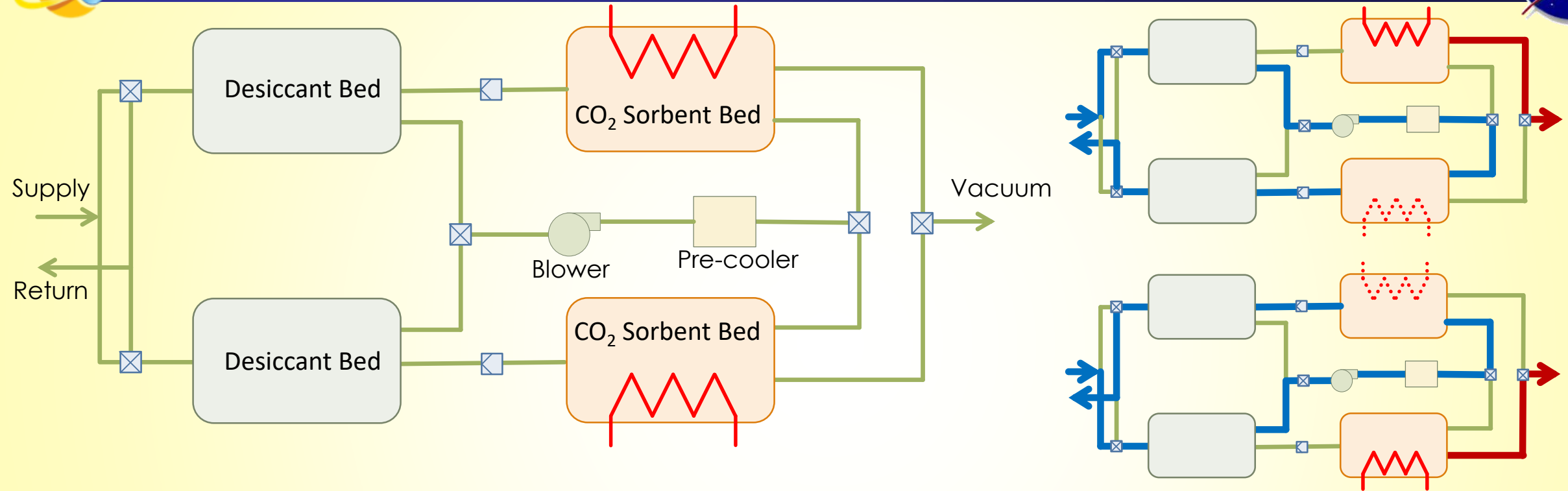
4BMS-X Heater Core Design Requirements/Goals



- The primary heater sizing and design requirements established for this study are half cycle time, target temperature and the desire to minimize thermal gradients and flow channeling.
- The desired half cycle time is 80 minutes with an initial ramp time of 60 minutes.
- The desired target temperature is 200 °C which represents an average bed temperature.
 - In the baseline 4BMS-X design the sorbent bed is driven to higher temperature than is necessary to desorb CO₂ from zeolite 13X (baseline sorbent) as the sensible energy of the effluent gas is also used to help desorb water vapor from the downstream desiccant bed.
- Minimizing thermal gradients in the sorbent bed will increase efficiency as well as potentially mitigate pellet dust formation resulting from thermal expansion.
 - A specific thermal gradient is not defined but a lower temperature limit of 150 °C in the bed is desired to facilitate CO₂ desorption and an upper limit within +10°C of the target temperature is desired to mitigate dust formation.
- Channeling is not quantified in this effort but qualitative assessments on heater fin geometry and surface area that could exacerbate channeling are made.



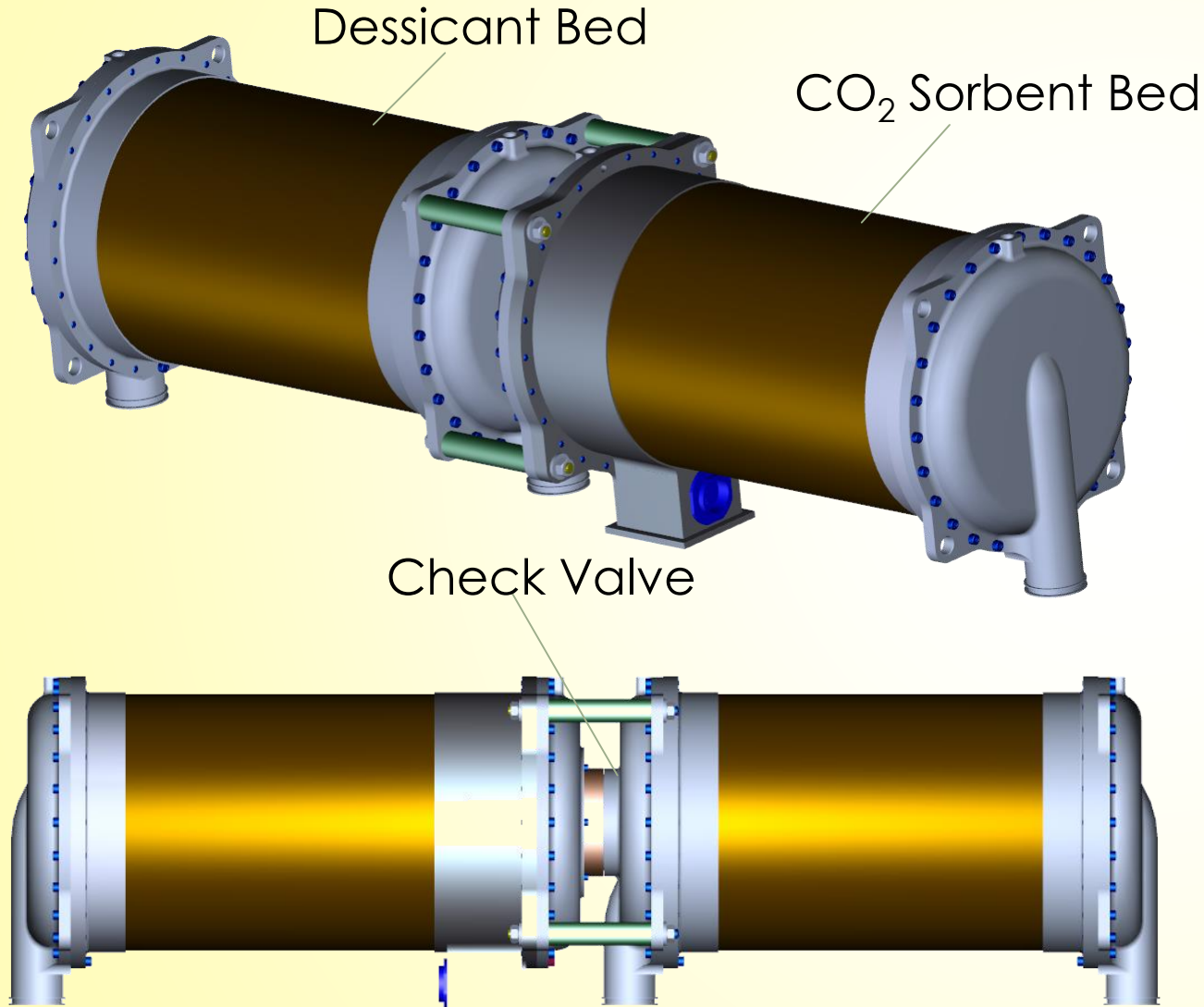
4BMS-X Process Technology



- The 4BMS-X contains two pelletized adsorbent beds to remove CO₂ respired by the crew. Each CO₂ adsorbent bed is paired with an upstream desiccant bed to condition the inlet air (i.e. remove water vapor) prior to entry into the adsorbent bed.
- While one adsorbent bed is actively capturing CO₂ at near ambient pressure, the other is regenerated through applied heat and partial vacuum desorption.



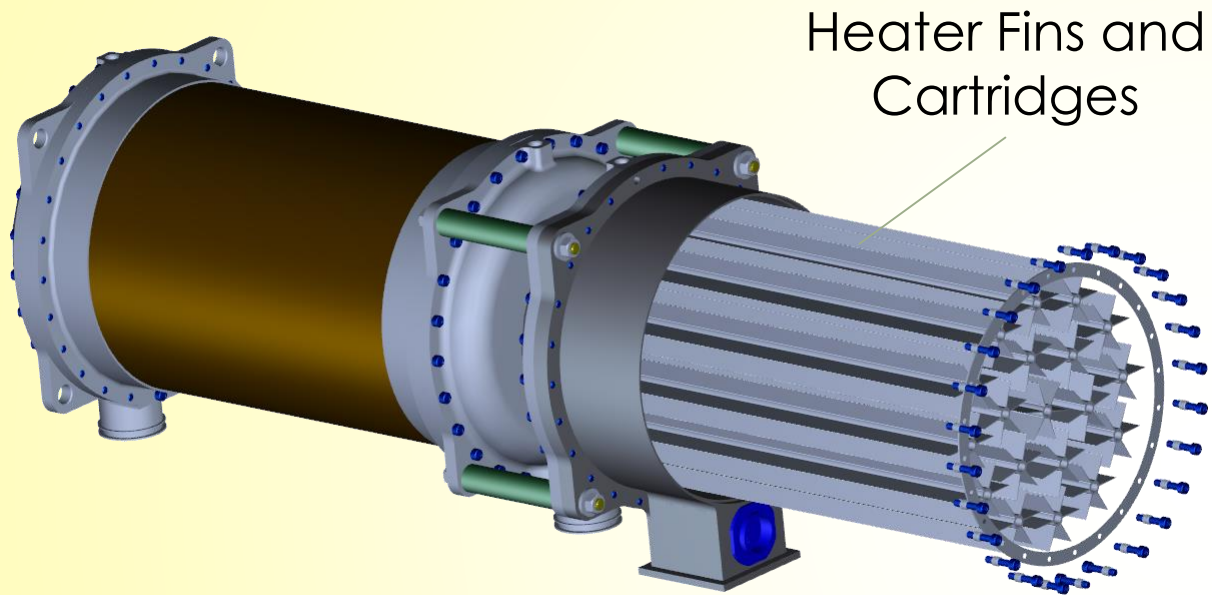
4BMS-X Conceptual Design



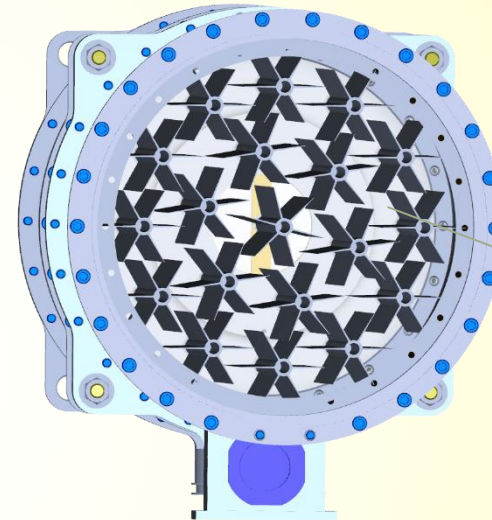
- The 4BMS-X beds are cylindrically shaped following industrial practice for fixed beds to insure the sorbents are fully compacted and to minimize heat transfer to the surroundings.
- Each cylindrical housing is constructed from Aluminum 6061 and is comprised of two end caps, mating flanges and a barrel section to contain the sorbent material.
- The two cylindrical beds are mated together through a common flow path containing a check valve between the beds.
- Each bed is insulated with a $\frac{3}{4}$ inch layer of Pyropel LD6 thermal insulation.
- The inside diameter and length of the CO₂ sorbent bed are 8" and 12" respectively.



4BMS-X Conceptual Design utilizing Star Shaped Heater Fins



Heater Fins and Cartridges

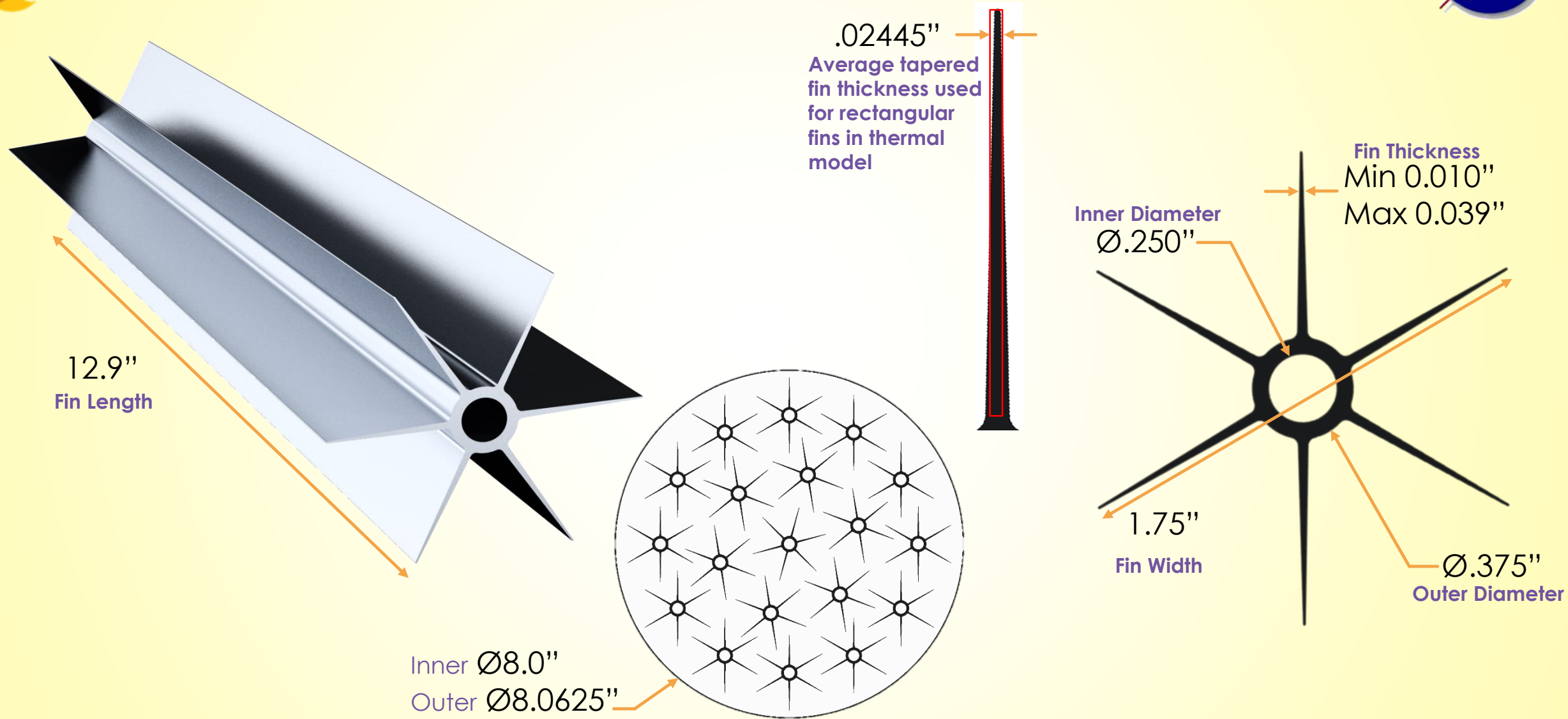


End View
Void Spaces
filled with
Sorbent

- The CO₂ sorbent bed container is removed to expose the heater core and associated fins. Each fin assembly has a 0.25" penetration in the base to accommodate a cartridge heater (not shown).
- Each fin assembly with embedded cartridge heater is mounted (cantilever) into an end plate inside one of the sorbent bed end caps.



4BMS-X Heater Fin Design

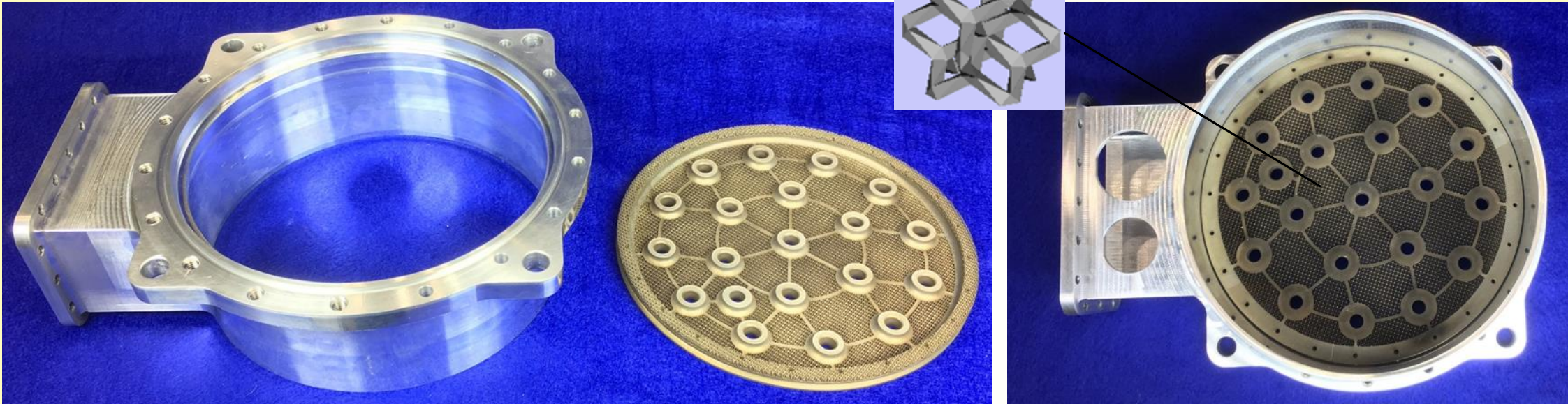
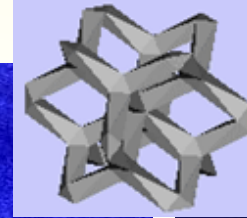




4BMS-X Heater End Plate



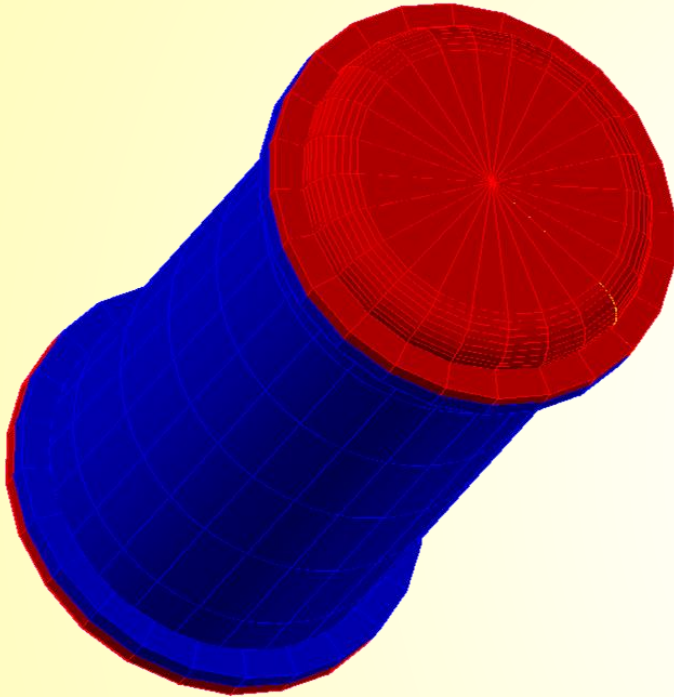
Dode-Medium



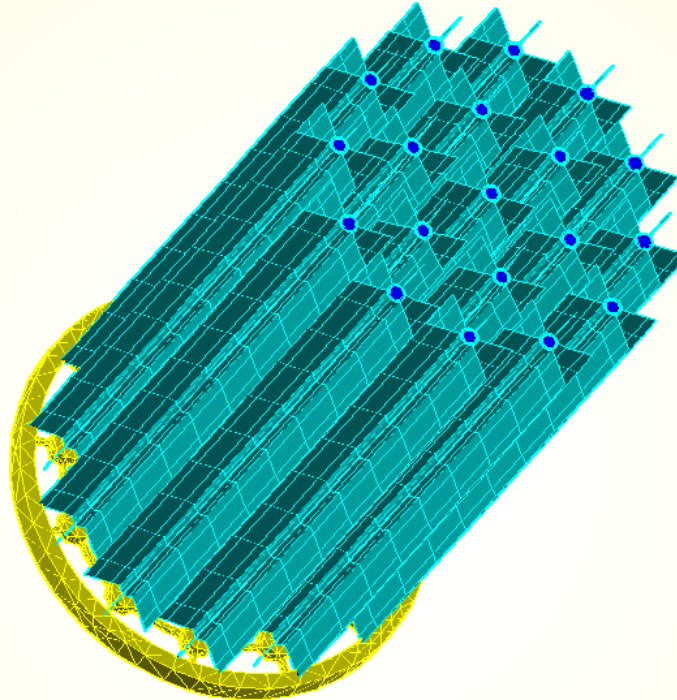
- The end plate is produced through an additive manufacturing process with a lattice filled spacing between cartridge heater mounting holes.
- The lattice provides structural strength while minimizing thermal conductivity (due to the void space inside the lattice).
- The end plate mounts on a flange inside one of the 4BMS-X sorbent bed end caps as shown.



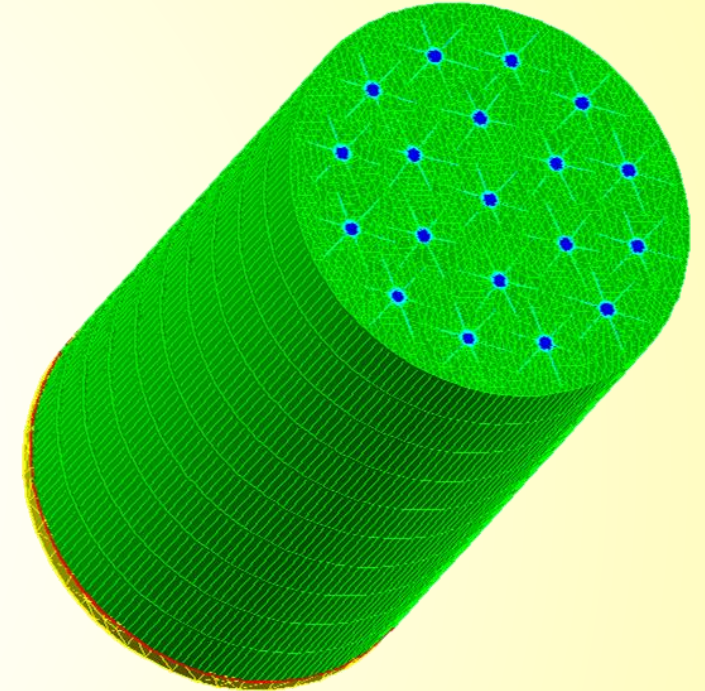
4BMS-X Sorbent Bed Thermal Model



External Container



Heater Core and Mounting Plate

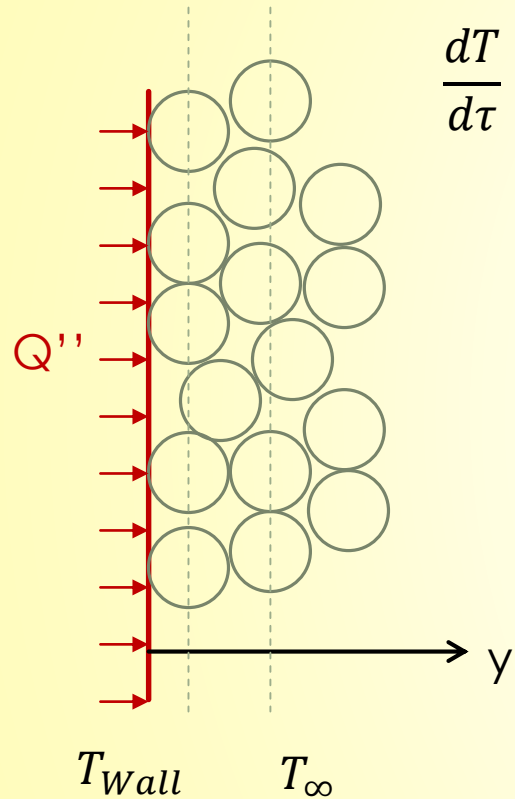
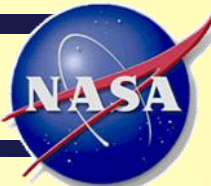


With Sorbent Material

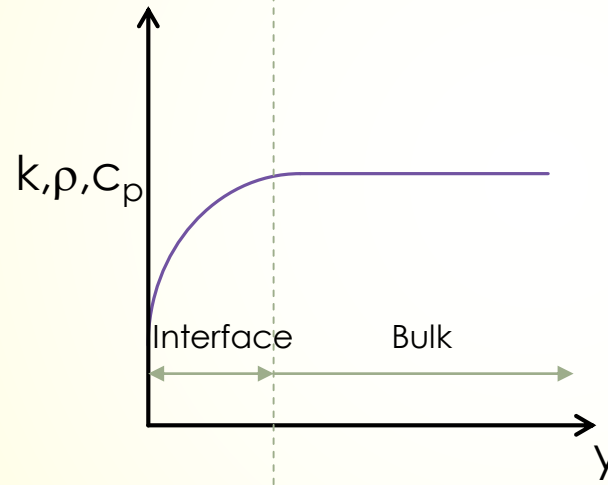
- The Thermal Desktop® 4BMS-X 3D thermal model contains over 50,000 nodes with execution times on the order of 5 minutes for a 60 minute transient simulation.
- The sorbent volume (green) is discretized into finite element wedges and fits inside the external container model with a thermal contact coupling between the sorbent and container. Likewise, the heater assembly fits within the sorbent model with a contact coupling between the fins and the sorbent.



2D/3D Packed Bed Modeling Approach



$$\frac{dT}{d\tau} = \alpha \nabla^2 T \quad \text{where} \quad \alpha = \frac{k}{\rho c_p}$$

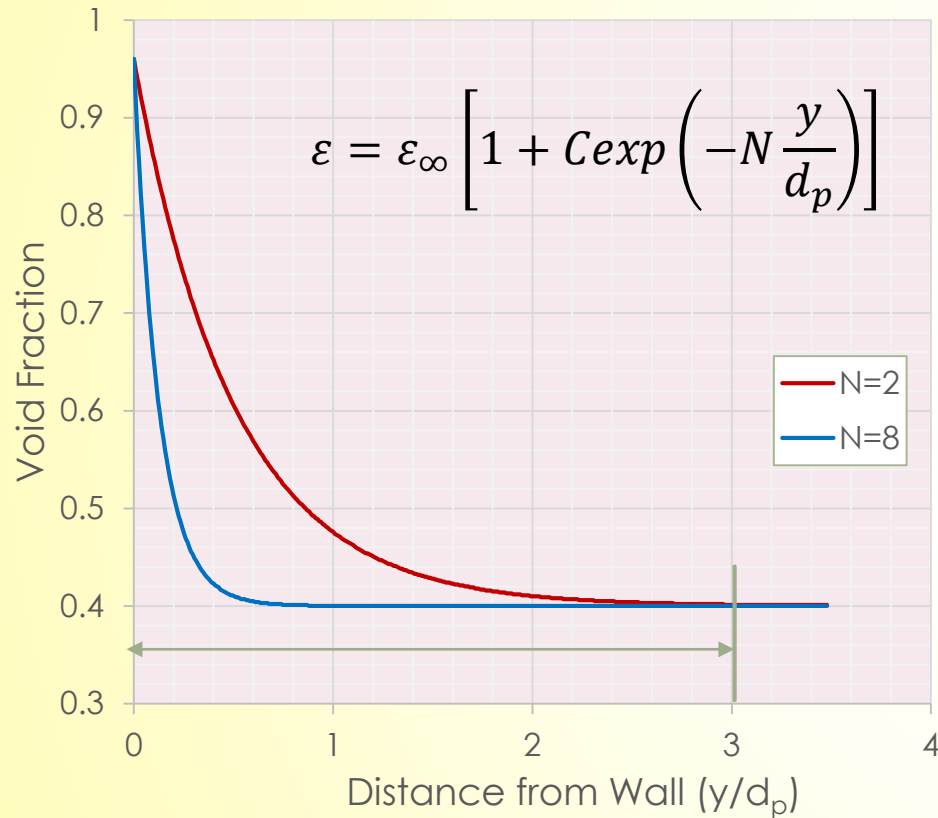


- During vacuum/thermal desorption of CO₂ sorbent beds, the transient thermal response is dependent on the thermal diffusivity of the bed.
 - Radiation more significant with increasing temperature.
- A modeling approach is proposed where a thin interface region (of high diffusivity) near the wall is modeled as a thermal resistance with bulk properties used deeper in the bed.
- Thin interface region doesn't participate in energy storage (thermal diffusivity gas \gg solid) but the thermal coupling is modeled via boundary condition or thermal contact.
- Thermal mass of any heater mounting structure also very significant.



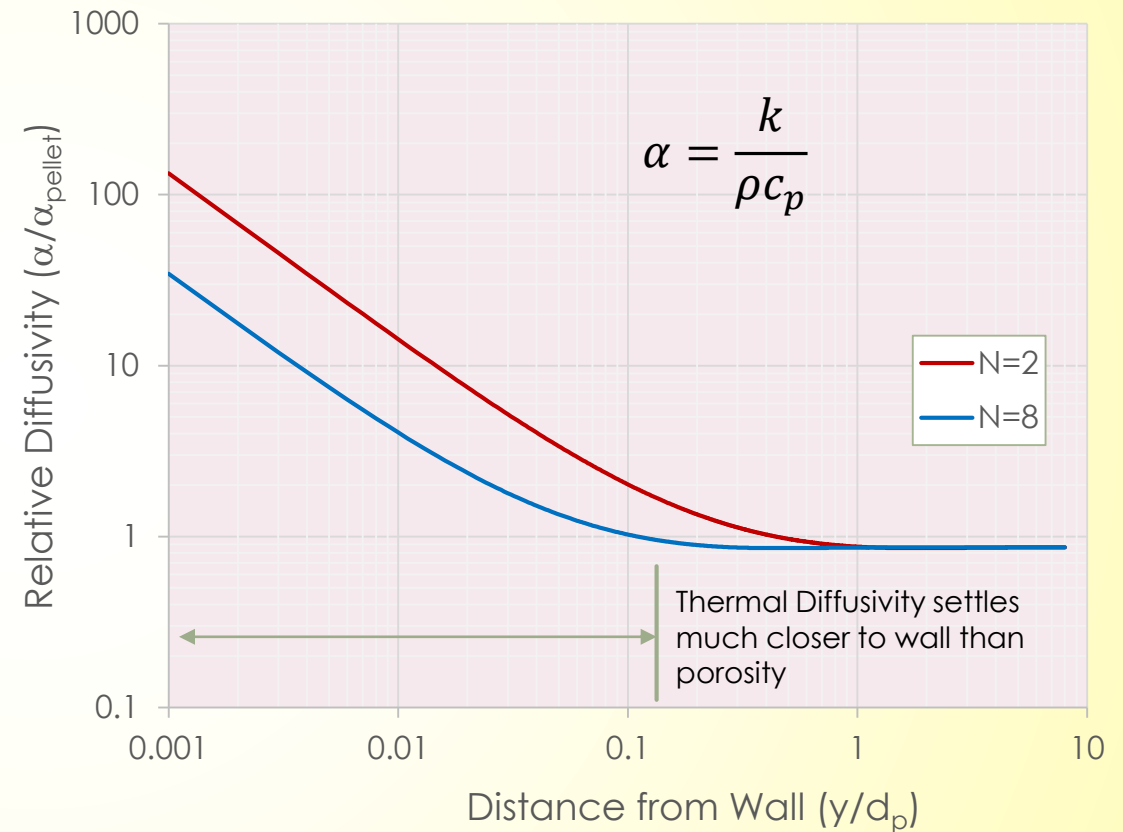
Porosity Assumptions at Packed Bed Wall

Void Fraction versus Relative Distance from Wall



*Nield and Bejan, 1992; N=2,...8

Thermal Diffusivity versus Relative Distance from Wall





Thermal Interface Coupling



$$Q'' = -k \frac{dT}{dx}$$

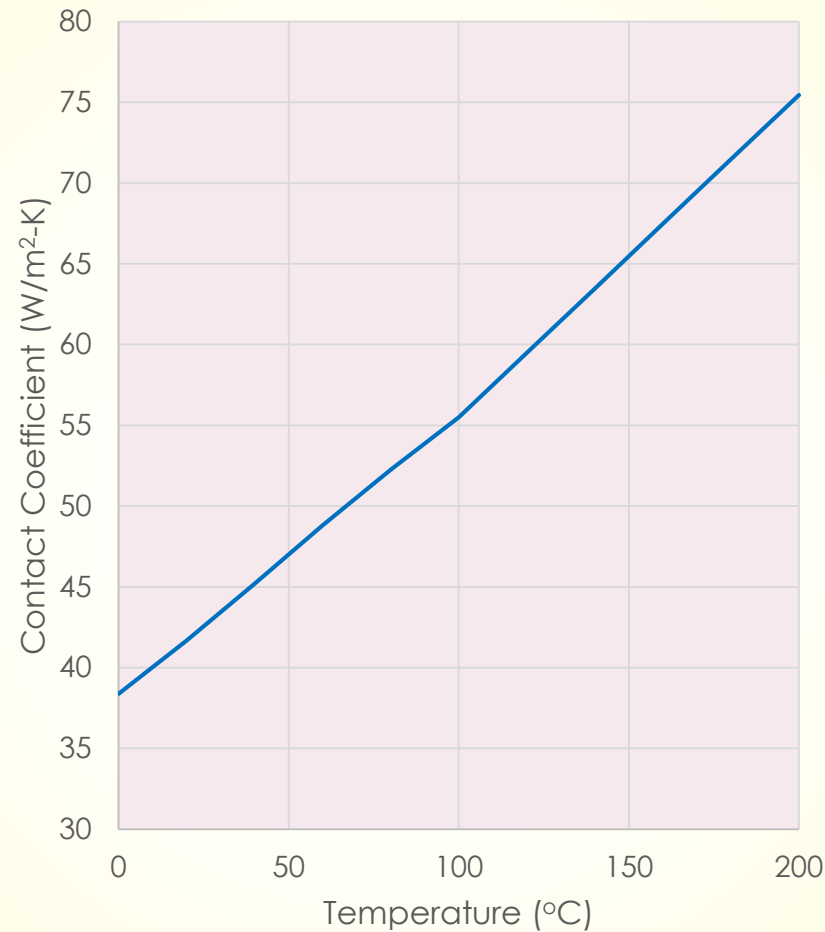
$$Q'' \frac{dx}{k} = -dT$$

$$Q'' \int_0^L \frac{dx}{k} = - \int_{T_{Wall}}^{T_{\infty}} dT$$

$$Q'' \int_0^L \frac{dx}{k} = (T_{Wall} - T_{\infty})$$

$$Q'' = \left(\int_0^L \frac{dx}{k} \right)^{-1} (T_{Wall} - T_{\infty})$$

$$Q'' = h(T_{Wall} - T_{\infty})$$

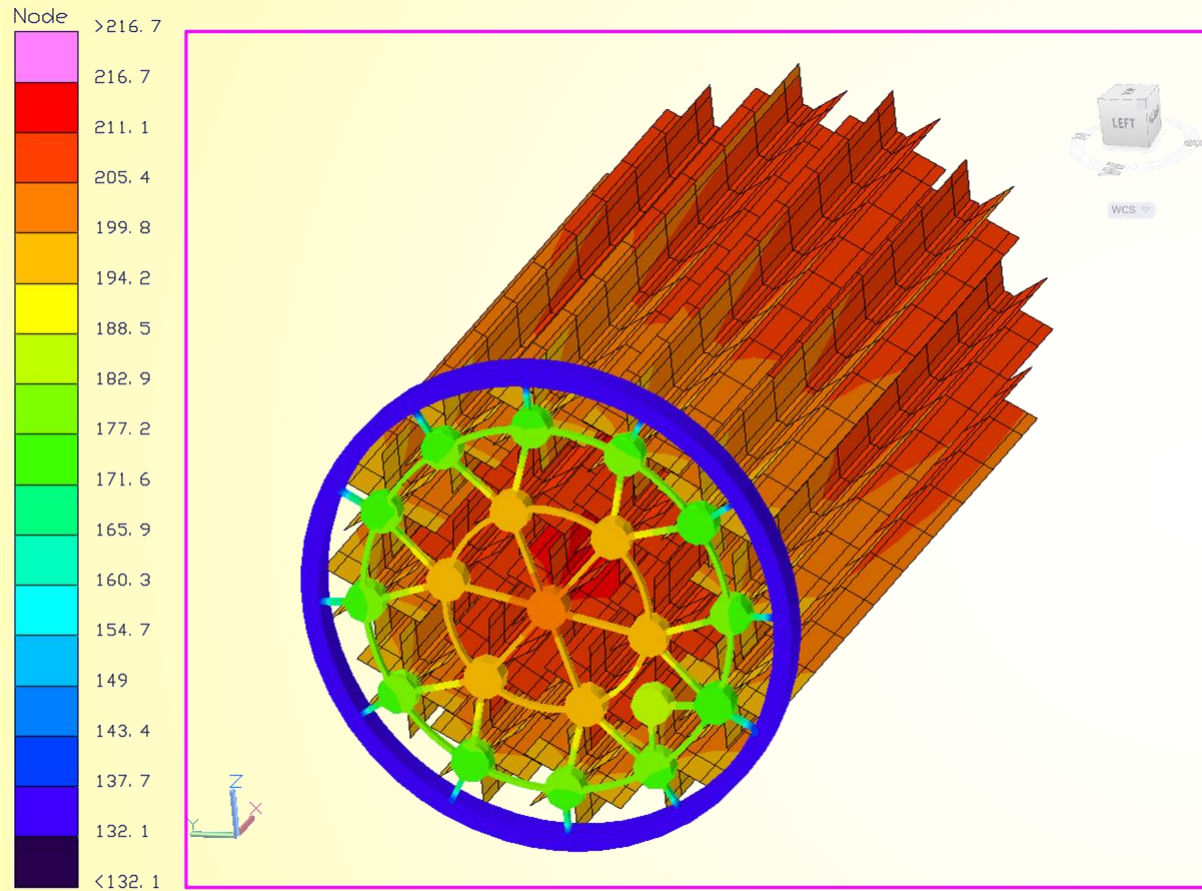


$$h = \left(\int_0^L \frac{dx}{k} \right)^{-1} \quad k_{eff} = L \left(\int_0^L \frac{dx}{k} \right)^{-1}$$

- Fourier 1D heat conduction equation is integrated to determine equivalent “h” that is dependent upon depth of the interface layer.
- Coupling is shown versus depth of the interface layer.

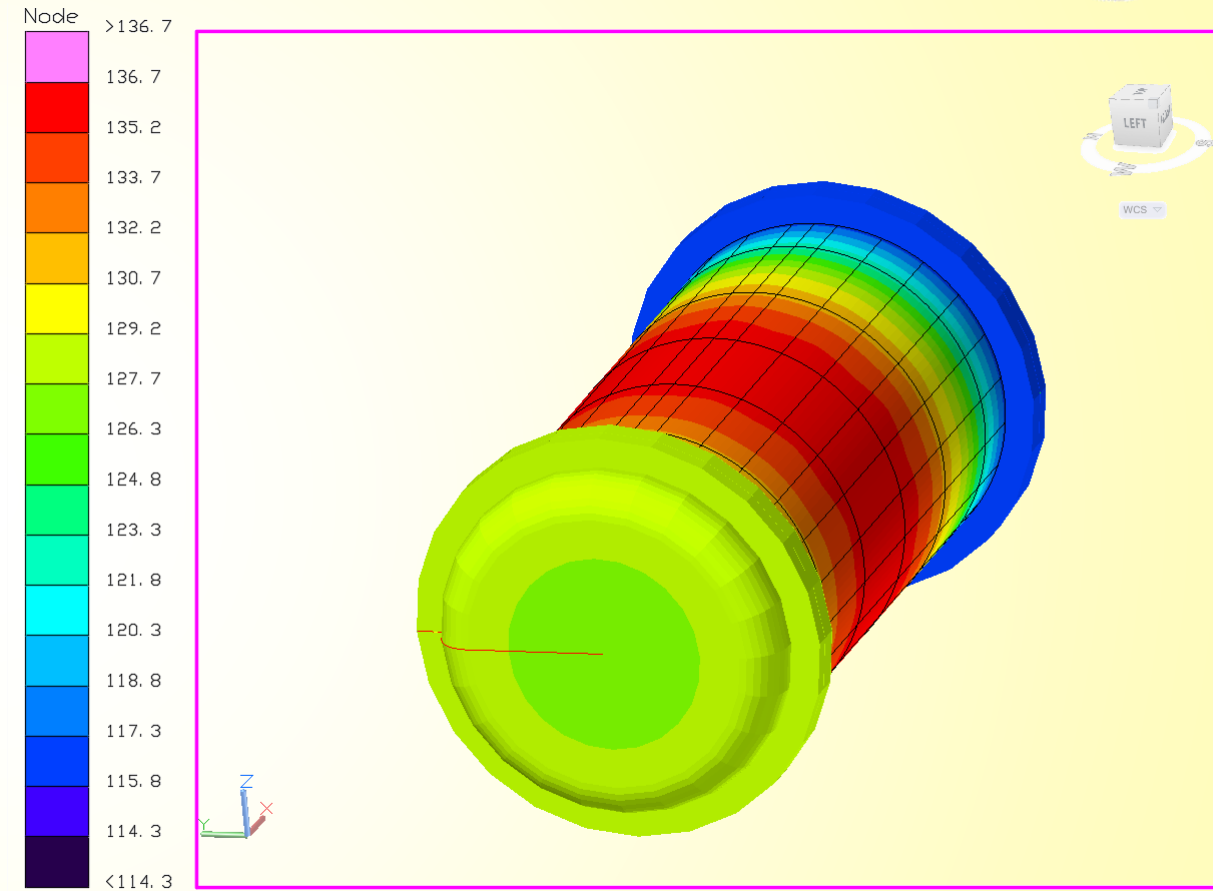


4BMS-X Predicted Temperature Profile



Temperature [C], Time = 3600 sec

Inside- Heater Core and Mounting Plate

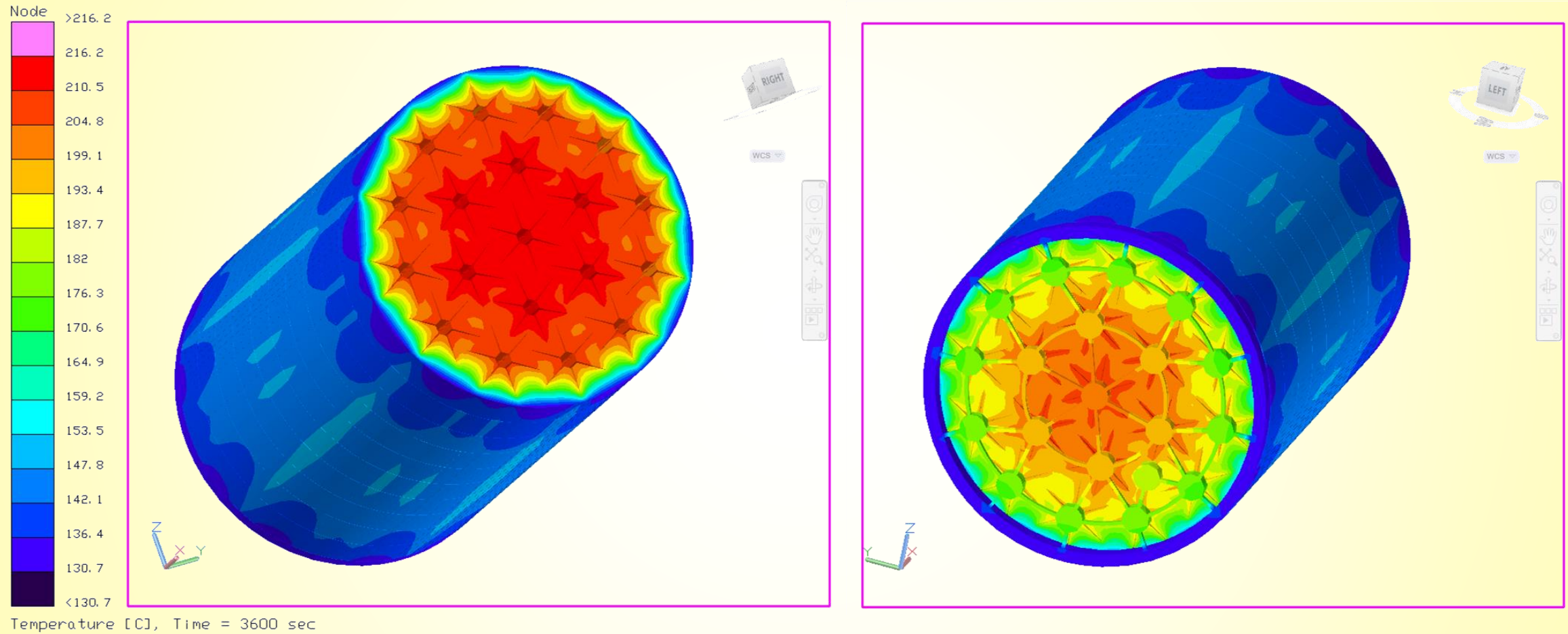


Temperature [C], Time = 3600 sec

Outside- Container



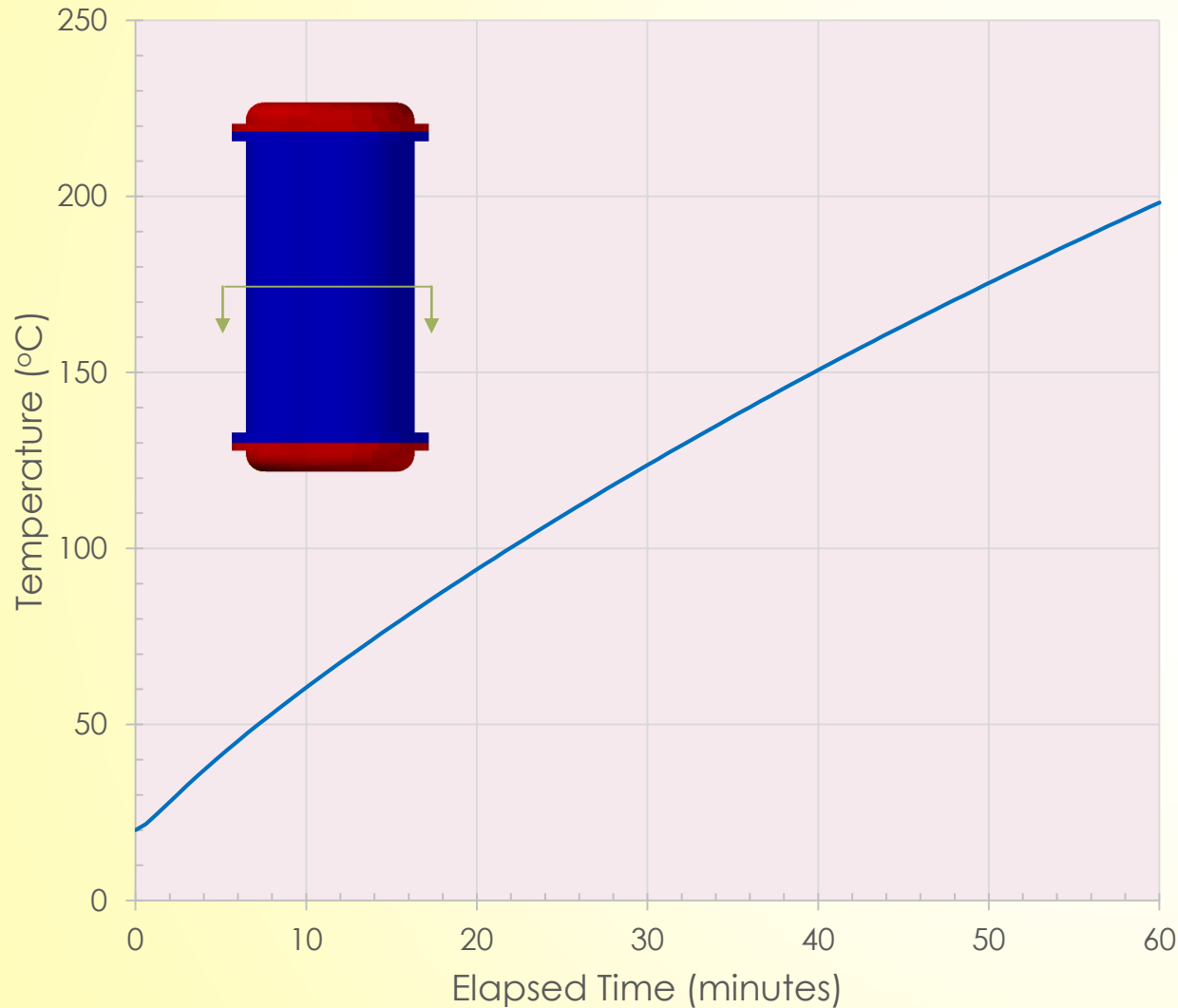
Sorbent Bed Temperature Profiles





4BMS-X Sorbent Bed Transient Profile

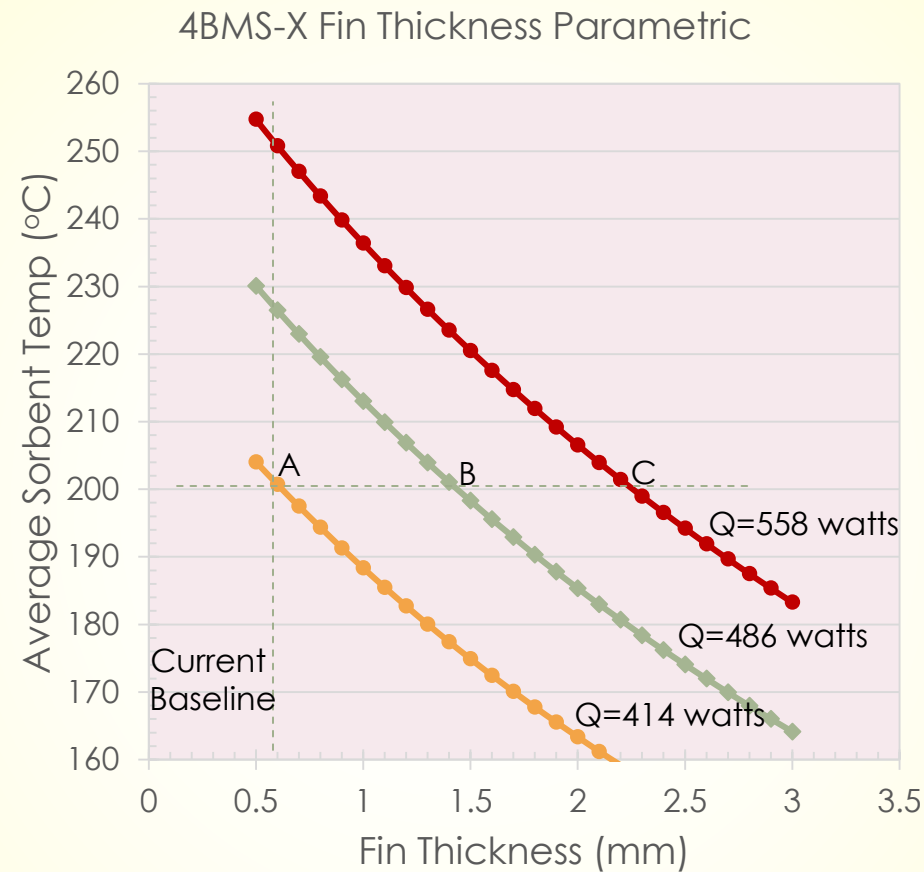
Average Sorbent Bed Temperature-Mid Plane



- The predicted transient profile for the cross section of a 4BMS-X sorbent bed is shown.
- The average temperature of the cross section reaches a target value of 200°C in 60 minutes.



Parametric Results: Average Bed Temperature vs Fin Thickness

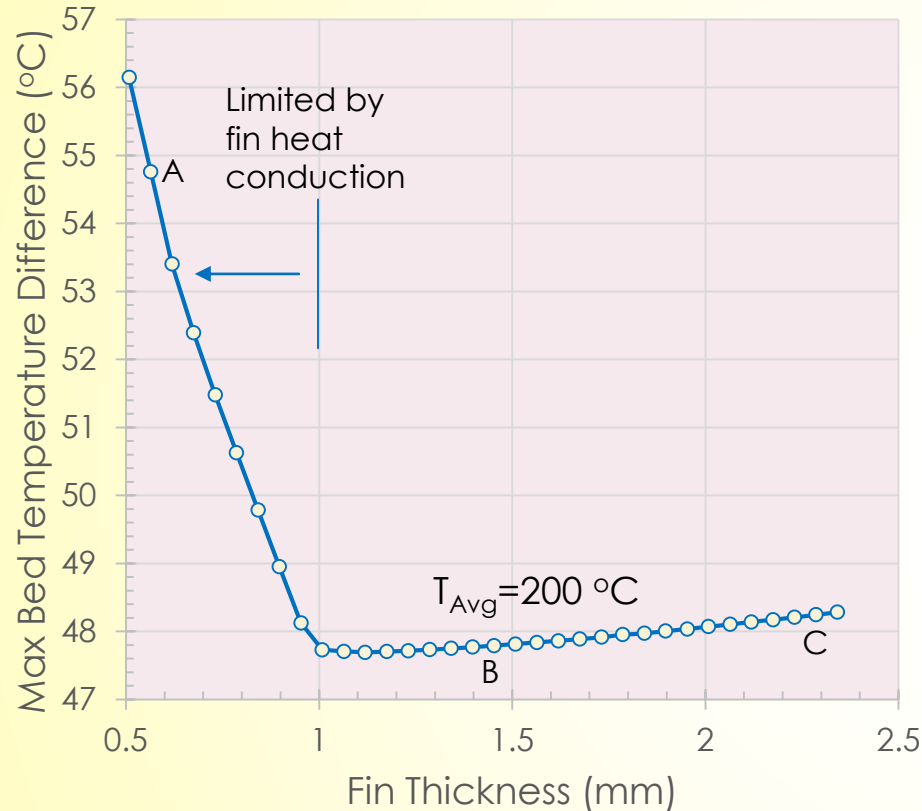


- Transient results at 60 minutes. Current (average) fin thickness is 0.02445 inches (or 0.62 mm).
- Increasing fin thickness lowers the average sorbent temperature at constant heater power due to better heat distribution and increased thermal mass of the fin.

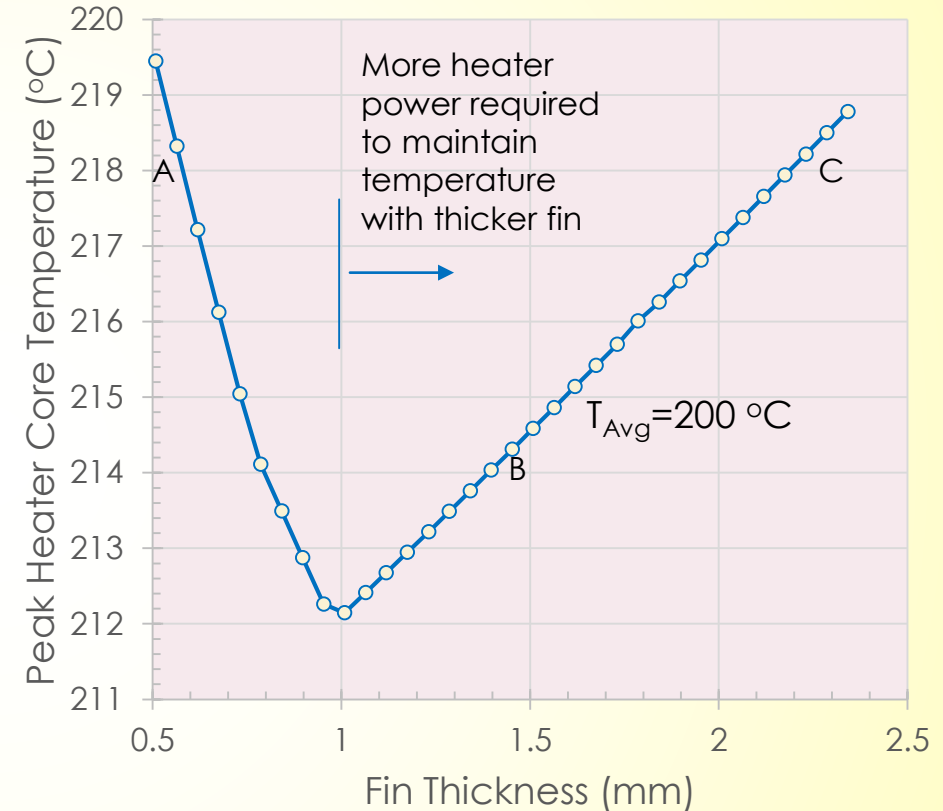


Parametric Results: Average Bed Temperature vs Fin Thickness

4BMS-X Isothermal Bed Parametric



4BMS-X Peak Heater Core Temperature



- Heater sized to achieve target bed temperature (i.e. heater dissipation increases with fin thickness).
- Limited by fin heat conduction below the inflection point. Increased thermal mass of the fin above the inflection point requires more heater power to maintain temperature.



Summary and Future Plans



- A design and heater optimization study for 4BMS-X CO₂ sorbent beds in a proposed exploration system architecture has been completed.
- An analytical approach to predict the contact conductance between sorbent materials and solid surfaces based on empirical void fractions was developed.
- Two dimensional models of the baseline concept with roughly equidistant cartridge heaters/fins show thermal gradients confined mostly to the edges of the circular container with a roughly isothermal center section.
- Parametric studies with the two dimensional models show an optimum fin thickness with respect to gradient and heater power. Future designs may benefit from this optimization.
- Three dimensional thermal models of the baseline concept identified axial thermal gradients caused by heat loss through a conductive heater mounting plate.
- Additive manufacturing of the end plate to produce custom geometries may be used to further reduce the thermal gradient.
- Thermal model correlation to test data will be the highest priority for future work.



Acknowledgements

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